UNCONTROLLED DIFFUSIVE BURNING OF SOME NEW LIQUID PROPELLANTS

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INTRODUCTION

The safe use of new liquid fuel-oxidizer combinations for rockets requires evaluation of the hazards that may result from accidental spillage and ignition. One such combination is based on hydrazoid and amine type fuels--consisting essentially of mixtures of unsymmetrical dimethyl hydrazine (UDMH) and diethylenetriamine (DETA); the mixtures are designated as MAF-1 and MAF-3; MAF-1 is (by weight) 41 percent UDMH, 9 percent CH_3CN, and 50 percent DETA; MAF-3 is 20 percent UDMH and 80 percent DETA. Materials of this type present special problems in fire fighting. They are water-soluble, possibly toxic, and more likely to be chemically reactive with their environment or fire extinguishing chemicals than common hydrocarbon fuels. Fires of these new fuels may be less readily extinguished by common extinguishing agents. Deep pools of blended fuels may boil over during burning, etc. Laboratory scale techniques for evaluating such hazards and defensive measures are obviously useful. This paper reports techniques (and results) which were developed and which should be extendable to other similar fuel-oxidant systems. These techniques were used to measure burning rates of large pools of fuels, radiation from flames, temperature profiles in flames and liquid beneath, composition of combustion products, and limits, in terms of water dilution, of fire points and of hypergolicity.

MEASUREMENTS AND DISCUSSION

Burning Rates in Large Pools

Single-Component Fuels

Judging by the work of Blinov and Khudiakov (1, 5) and our own more extensive work with other single-component fuels (2, 13), the burning rate of a fuel in shallow trays approaches constancy as the tray diameter increases (Fig. 1). Burning rates taken with trays about a meter or two in diameter can be extrapolated to yield burning rates in very large trays. This extrapolation for single-component fuels and the basis for it are discussed in references 2 and 13. As explained in these discussions, the burning rates of single-component liquid fuels in large pools, v_∞, in centimeters per minute, is given by equation 1:

$$v_\infty = 0.0076 \frac{\Delta H_{comb.}}{\Delta H_{vap.} + \int_{T_a}^{T_b} C_p \, dt} \qquad (1)$$

where $\Delta H_{comb.}$ is the "net" heat of combustion and $\Delta H_{vap.}$ is the heat of vaporization at the boiling point, T_b. The integrated heat capacity in the denominator determines the temperature dependence of burning rate, normally about 1/2-percent per degree

Centigrade variation of the initial liquid temperature, T_a. The dependence of burning rates of such fuels on thermochemical properties is shown by Table 1 (2, 13). Values for UDMH and DETA are included in Figure 1 and Table 1.

Blended Fuels

Fires of pools of blended fuels, especially those whose components differ widely in their volatility, do not burn with a uniform rate. In the beginning, the burning rate is characteristic of the more volatile component. During the middle portion of the burning, the less volatile component still must be brought to the boiling point of the blend. Finally as the fractionation proceeds the burning rate becomes characteristic of the higher boiling fraction. The burning rates of a blend are given by:

$$v_\infty = 0.0076 \left[\frac{n_1 \, \Delta H_{comb._1} + n_2 \, \Delta H_{comb._2} + \cdots}{n_1 \, \Delta H_{vap._1} + n_2 \, \Delta H_{vap._2} + \cdots + m_1 \int_{T_a}^{T_b} C_{p_1} dt + m_2 \int_{T_a}^{T_b} C_{p_2} dt + \cdots} \right] \tag{2}$$

where n_1 and m_1 refer to mol fractional composition in the vapor and liquid phases, respectively. For such blends as gasoline whose specific heats of combustion and of vaporization of the components are comparable and $n_1 \approx m_1$, equation 2 leads to a simple mixture rule:

$$v_\infty = n_1 v_1 + n_2 v_2 + \cdots \tag{3}$$

On burning an unleaded gasoline in a 122 cm. diameter tray we found a steady burning rate of 0.54 cm./min. From distillation data furnished by the supplier, the value given by equation 2 should be 0.57-0.60 cm./min. In the absence of distillation data covering compositions of liquid and vapor, equation 4 may be used for rough estimates of v_∞ or v for medium sized trays. The average burning rate of a 2:1 benzene-xylene blend in a 76 cm. diameter tray was given by equation 4 using experimental values for the individual burning rates of benzene and xylene (0.47 cm./min. (exp.) versus 0.48 cm./min (calc.)). Even for blends with components of widely separated boiling points, equation 3 yields rough estimates, except during the first and last stages of the fire. For example, the major components of MAF-1 and MAF-3 differ very widely in their volatility—UDMH boils at 63° C. and DETA at 207° C. However, for the 76 cm. tray and the 122 cm. tray predicted values exceed observed averages for the middle half of the burning time by about 15 percent for MAF-1 and about 50 percent for MAF-3.

Figures 2 and 3 confirm our analysis that for blends with appreciable concentrations of components of widely differing volatility, the initial burning rate is about that of the most volatile component and the final burning rate, about that of the least volatile. The radiation records in Figure 3 show that the steady burning rate for DETA was approached at the end of the burning of MAF-1 and MAF-3 in a 122 cm. tray.

Flame Radiation and Absorption

Radiation from flames and absorption of radiation by fuel vapor and liquid affect the burning rate, as discussed in references 2 and 13. In addition, consideration of absorption of radiation by the liquid phase of the fuel or by water in the gaseous or liquid state is pertinent to attenuation of heat radiated to the liquid fuel or to the surroundings. About 24 and 28 percent of the heat of combustion was radiated to the surroundings by flames of UDMH, burning on the 76 and 122 cm. diameter tray, respectively (Table 2). Combination of photographic and radiation data gave

the magnitudes and variations shown in Table 3 in the specific radiation from such a flame.* The data in Table 2 can be used to compare the radiant flux from large UDMH and hexane flames of the same diameter; that is, ratio of linear burning rates × ratio of liquid densities × ratio of heats of combustion × ratio of percentages radiated =

$$\left(\frac{7.0 \text{ mm./min.}}{3.5 \text{ mm./min.}}\right)\left(\frac{0.66 \text{ gm./cc.}}{0.78 \text{ gm./cc.}}\right)\left(\frac{11.5 \text{ kcal./gm.}}{7.9 \text{ kcal./gm.}}\right)\left(\frac{42\%}{26\%}\right) \approx 4.$$

A fourfold reduction in radiation level compared to hydrocarbon flames should be a significant factor in safety considerations.

Furthermore, data in Table 4 and Figure 4 show that UDMH and MAF flames resemble flames of methanol more nearly than those of benzene with regard to self-absorption of radiation from their respective flame. Liquid UDMH and the MAF's are good self-absorbers since a depth of 0.3 cm. of liquid absorbs about all the radiation.

An additional factor to be considered is the absorption of flame radiation by atmospheric water vapor. When a flame is only weakly luminous, its emission spectrum may differ from that of a black body, a large proportion of the energy being emitted within the emission bands of water and carbon dioxide. This energy is susceptible to absorption by atmospheric water and carbon dioxide, and in the case of hydrogen fires or methanol fires, atmospheric absorption is a factor to be considered. In the case of UDMH and MAF fires (Table 4), absorption of radiation by water vapor roughly follows Lambert's law for the two shortest pathlengths of water vapor but not for the whole range up to 37 cm. This means that radiation from UDMH and MAF fires cannot be blanketed by long distances through moist air.

Temperature Profiles in Flames and Liquid; The Boilover Problem

Temperatures observed underneath a small UDMH diffusion flame and at its surface are given in Table 5. A flame burning on a 50 mm. diameter petri dish and standing about 23 cm. high was probed with a ceramic coated (NBS ceramic A-418) platinum platinum-10 percent rhodium unshielded 10 mil thermocouple. It is apparent that high temperatures (about 600° C.) are obtained in the unburned gas about a centimeter or so above the liquid (liquid level was about a centimeter below the rim of the dish). Maximum temperatures at the flame front are about 1100° C. Similar temperatures have been observed in diffusion flames of hydrocarbons (10, 11, 12), and of alcohol, benzol, petrol, and kerosene (8). Calculations of adiabatic flame temperatures for premixed flames are given in Table 6 for comparison with values observed in the diffusion flame. The temperatures observed in the gas phase beneath the diffusion flame of UDMH are consistent with the radiation measurements showing self-absorption of flame radiation. The radiation absorption measurements also showed that the liquid absorbed strongly and so a steep temperature gradient is to be expected at the liquid surface of burning UDMH. Such steep gradients were observed at the liquid surfaces of fires of UDMH and DETA. Conceivably, such hot layers at the surface of a burning deep pool of MAF-1 or MAF-3 may cause violent bumping and splashing of burning fuel. Violent expulsion of fuel (called "boilover") may occur with oil tank fires, due generally to an immiscible layer of water below the oil, which is suddenly converted into steam (4, 9).

*Cycling of flame size may be due to partial self-smothering which causes the flame to lengthen. This lengthening of flame improves the diffusion and entrainment of air, causing the flame to shorten. Evidence for this explanation of fluctuating flame size comes from studies of smoke limits of flames in ethylene-air mixtures. Limit flames only emitted smoke when the flame was in the tallest stage (3).

Somewhat different circumstances than with oil fires may lead to boilovers with the MAF's--a mechanism involving instabilities of convection currents in the liquid. Consider that at room temperature the density difference between high and low boiling components is more extreme in UDMH-DETA blends than in most hydrocarbon blends, and that the viscosities of DETA and of UDMH-DETA blends are quite comparable to the viscosities of higher hydrocarbons. A hot, metastable layer may therefore form at the surface of a deep, burning pool of MAF and suddenly fall to the bottom, boiling out UDMH from cold bottom layers. For this to occur, a considerable mass of metastable hot liquid must gather at the surface. Otherwise such a layer would not contain much heat, and as it fell it would only accelerate the heat front downward; it could not produce a boilover. However, if the gravitational forces downward were almost counterbalanced by the viscous forces holding the layer in place, a large mass might accumulate at the surface. Secondly, boilover is possible only if the density of the hot liquid at the top is greater than the density of the initial liquid. Thirdly, the likelihood of boilover increases if the viscosity of the hot liquid is equal to or greater than that of the initial liquid. If the hot layer falls and the viscosity of the hot liquid is less than the viscosity of the initial liquid, viscous shear will tend to disperse the hot liquid and prevent the sudden transport of much heat to the bottom layer. The data in Table 7(A) indicate that there is no danger of boilover due to accumulation of boiling DETA at the surface. Table 7(B) indicates that boilover is potentially possible as long as the surface layers atop cold MAF-1 are colder than about 120° C., and those atop cold MAF-3 are colder than about 60° C. In Table 7(C), a comparison is based on 60° C., the approximate temperature at which MAF-1 and MAF-3 start to distil. Hot surface layers of DETA up to about 160° C. appear to be metastable compared to MAF-1 at 60°, and correspondingly up to about 100° C. for MAF-3. The temperature difference for MAF-1 (158-60°) is about two and one-half times that for MAF-3, about the same as for the comparison in Table 7(B). It appears, therefore, that if metastable layers form atop either MAF-1 or MAF-3, the heating potential in the MAF-1 case is more than double that in the MAF-3 instance. On the basis of these analyses, a boilover with MAF-3 is far less likely than with MAF-1.

Experiments were performed with MAF-1 and MAF-3 in which 38 kg. of MAF-1 and 47 kg. of MAF-3 were burned in an instrumented drum measuring 30 cm. in depth and 47 cm. inside diameter. Temperature profiles as a function of time are given in Figures 5 and 6. The history of selected isotherms is given in Figures 7 and 8. The temperature profiles were observed by means of thermocouples in the liquid (at about 0.6 radius from the wall). Temperature-sensitive paints on the sides of the container were also used. In general, thermocouples and paint showed about the same rate of heat travel. Figures 5 and 6 show that a temperature inversion at the bottom of the tank occurred with MAF-1 but not with MAF-3. Figure 7 shows that the heat front moving downward through MAF-1 accelerated during burning from about 0.2 cm./min. to about 0.8 cm./min. Figure 8 shows that the heat front moved steadily downward in MAF-3 at about 0.14 cm./min. The acceleration of the travel of heat front through MAF-1 started after about an hour of burning. After 1-1/2 hours of burning, the temperature paints showed that the bottom of the container was at least at 65° C. About the time this heat front reached the bottom of the tank, a vigorous foaming suddenly started and continued for approximately 10 minutes. No appreciable head of foam was apparent, nor was there any bumping of the liquid. Thereafter, as it did before, the liquid bubbled smoothly and quietly over its entire surface until burnout. As soon as the foaming stopped, a sample of fluid was withdrawn through a tap 5 cm. from the bottom and about 10 cm. from the top of the liquid. The specific gravity of this sample was 0.94 at 27° C., about equal to that of DETA. Therefore, following the foaming all of the UDMH was gone from the MAF-1. Temperatures were fairly uniform throughout the liquid, and were about 165° to 175° C. About 5 minutes before the foaming started, temperatures were above 140° C., except for the bottom 8 cm. of liquid which was around 65-70°C. Within these 5 minutes, temperatures in the bottom 8 cm. rose above 140°. These temperatures are in fairly good agreement with temperatures listed in Table 7 for MAF-1. MAF-3 burned smoothly. The only novel observation was the appearance after a

couple of hours of burning of very fragile brown clots. Although the observed foaming did not raise or throw liquid, its occurrence, the data in Figures 5 and 7, and Table 7 all indicate that boilovers or perhaps only foaming are possible with MAF-1. The weight of experimental and theoretical evidence indicates that boilovers are unlikely with MAF-3.

Composition of Combustion Products

As shown in Tables 8 and 9, samples drawn from UDMH diffusion and premixed flames contain hydrogen cyanide, methyl cyanide, and carbon monoxide. A few centimeters past the flame surface of diffusion flames, these toxic gases are absent. DETA produced as much as 1.5 percent of hydrogen cyanide on combustion. Therefore, fumes from incompletely burned UDMH, DETA, and the MAF fuels may be unusually toxic. Observed flame temperatures in Table 9 are in good agreement with calculated temperatures in Table 6.

Fire Points of Aqueous Solutions

Water is the least expensive and generally most readily available extinguishing agent for fires of MAF fuels. Foam has to be specially prepared and is rapidly disintegrated. Other extinguishing reagents are expensive or soluble or reactive. To evaluate water requirements for fighting fires of the MAF's, measurements were made of the water dilution necessary to render nonflammable aqueous solutions of UDMH, MAF-1, and MAF-3. About two volumes of water per volume of fuel suffice for this purpose. (For very deep pools, less water will be required if only the upper portion of the tank's contents has to become nonflammable.) The data are given in Table 10 along with dilutions needed for some alcohols and acetone. The ratios in the last column of Table 10 of heat of vaporization to heat of combustion indicate that the water requirements can be simply estimated, without recourse to measurement. At worst, the estimate provided a fivefold safety factor and for three of the seven tests provided good agreement with experiment. The estimate is based on the assumption that an aqueous solution of a fuel will not burn when the heat of combustion of the solution equals the heat of vaporization at the boiling point of the liquid, that all of the heat of combustion is transferred to the liquid and the compositions of vapor and liquid phases are identical. Errors due to the last two assumptions tend to neutralize each other with regard to the prediction of water concentration at the fire point. It is obviously difficult to compute the heat transfer from flame to liquid. It is also questionable whether vapor phase composition can be computed accurately enough using the liquid composition. Figure 9 shows that equilibrium between compositions of the liquid and the vapor burning above it may not be assumed near the fire point. Equilibrium curves were taken from the literature (6). Experimental points were obtained by adding an arbitrary mixture of methanol-water, e.g., 1:1 on a molar basis, to a burning methanol pool. The rate of addition was such as to maintain a constant weight of liquid. Eventually the composition of the liquid, as determined by specific gravity measurements, became constant. (There were no significant concentration gradients in the body of the liquid.) At this stage the composition of the mixture being distilled by the flame was identical to that of the mixture being added.

Hypergolicity of Aqueous Solutions

Since the MAF fuels would typically be used with such oxidants as inhibited red fuming nitric acid (IRFNA) there are special problems of preventing hypergolic ignition on simultaneous spillage of fuel and oxidant. It was observed that when the vapors above UDMH and above RFNA were permitted to interdiffuse in a particular closed apparatus at 28° C., there was no ignition. On raising the temperature to 38° C., ignition occurred. Vapors above either MAF-1 or MAF-3 ignited spontaneously with vapors from RFNA at 45° C. but not at 38° C. Impinging jets of the vapors at 60-100° C. in open air led to ignition despite precautions to eliminate liquid spray. Thus there is a need for newly obtained data on flammability limits and spontaneous ignition temperatures with air and inert gases as ignition-preventing diluents (7).

With regard to liquid phase interactions it was observed in preliminary spot-plate tests that ignition could be prevented by pre-diluting either the RFNA or the fuel (UDMH, MAF-1, or MAF-3) with 40 volume percent water and that DETA-RFNA were not hypergolic. These results were duplicated with 100 cc. quantities of propellant in dewars. To estimate the required water dilution for nonignition in large systems with no heat loss, the following conventional concept of hypergolicity was invoked:

(a) There are fast neutralization reactions, independent of the degree of dilution, yielding about 10-20 percent of the overall heat of combustion;
(b) The temperature of the system is thus raised sufficiently to permit slower reactions, such as oxidation or nitration, to lead on to ignition.

Accepting the neutralization step to be inevitable, one must dilute sufficiently with water so that the system never exceeds a critical temperature for initiation of second-stage reactions. Figure 10 shows the temperature rises obtained on adding water-diluted RFNA (50-50) incrementally to 200 cc. of water-diluted UDMH in a dewar, the diluted reactants having been precooled in each case to 25° C. Curves A, B, C, and D refer to 10, 20, 40, and 100 percent initial concentrations of UDMH and the dashed lines depict temperature rises from a hypothetical neutralization yielding 12 kcal./mole. In curves A and B the initial points are below predicted temperatures and heat evolution has virtually ceased when acid and UDMH are equimolar. However, in curve C, involving 50 percent acid and 40 percent UDMH, there is evidence of some additional reaction at the start and of heat evolution extending beyond the equimolar point. At about this dilution of reactants, and depending critically upon apparatus parameters, ignition was found to occur in the gas phase.

As best one can judge from the figure, the highest reaction temperature for safety in any conceivable environment would be about 50° C. From this, if the reactants are initially at 25° C., the minimum dilution should be about 8 grams of water per gram of UDMH-RFNA propellant. There is evidence that less water would be needed with the MAF fuels. For example, 100 cc. of (60-40) water-(MAF-1 or MAF-3) were mixed with 100 cc. (60-40) water-RFNA with a heat release that was judged to be 15 kcal./mole; 100 cc. of (50-50) water-MAF-3 were added to 100 cc. of RFNA, giving a heat release of 18 kcal./mole. In each case there was no ignition or evidence of delayed reaction.

CONCLUSIONS

The MAF fuels are similar in their gross burning characteristics to more conventional fuels. The hazards due to accidental fires of these materials appear to be manageable. As with hydrocarbons, radiative heat transfer is the dominant factor in the burning of large diameter pools. Burning rates are expressible as functions of the rates of the component fuels and are of the order of those of conventional fuels. Temperature profiles indicate that boilover during fires of deep pools is unlikely. About two volumes of water per volume of fuel results in a nonflammable solution. The products of incomplete combustion of the amines contain cyanides, a factor to be considered in fire fighting. Hypergolicity between the MAF fuels and red fuming nitric acid can be prevented by adding about two volumes water before mixing. The concepts used in this study should be applicable to other fuel-oxidant systems.

ACKNOWLEDGMENT

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Table 1.--<u>Relation of liquid burning rates to thermochemical properties of fuels.</u>

Fuel	ΔH_c (net) kcal./mol.	ΔH_v (sens.) kcal./mol.	$0.0076 \dfrac{\Delta H_c}{\Delta H_v}$	v_∞, cm./min.
Hydrogen	58.2	0.22	2.02	1.6
Butane	623	5.95	.81	.79
Hexane	916	9.77	.72	.73
Benzene	751	9.20	.63	.60
Xylene	1038	14.72	.55	.58
UDMH	432	9.53	.35	.38
DETA	735	26.1	.22	.20
MeOH	150	9.18	.13	.17

Table 2.--<u>Radiation by diffusion flames of liquid fuels.</u>

Fuel	Burner diameter, cm.	$100 \times \dfrac{\text{Radiative output}}{\text{Thermal output}}$
DETA	76	35
DETA	122	28
MAF-1	76	26
MAF-3	76	42

Table 3.--<u>Specific flame radiation from diffusion flame of UDMH. Pool diameter 76 cm.</u>

Time, minutes	Specific flame radiation,* watts/cm.^{2}
1.0	6.75
1.5	9.15
2.0	9.90
2.5	7.90
3.0	6.50
3.5	8.40
4.0	7.25
4.5	12.9
5.0	9.6
5.5	12.4
6.0	13.2
6.5	6.1

* $\dfrac{\text{Radiation output}}{2 \times \text{vertical cross section of flame}}$.

Table 4.--Transmission of flame radiation.

Flame of fuel	Cell length, cm.	Transmission, percent		
		Through water vapor at 165° C.	Fuel vapor at 100° C.	Fuel liquid
UDMH	0.3			1
MAF-1				1
MAF-3				0.3
UDMH	8.9	82	57	
MAF-1		89	61*	
MAF-3		81	65*	
DETA		--	--	
Methanol		87	73	
UDMH	18.4	72	49	
MAF-1		72		
MAF-3		76		
DETA		77		
UDMH	37	70		
MAF-1		69		
MAF-3		70		
DETA		69		

*Predominant vapor was UDMH.

Table 5.--Temperatures in a diffusion flame of unsymmetrical dimethyl hydrazine in air.

Tray diameter 50 mm., flame height about 230 mm.

Height above dish, mm.	Distance from axis, mm.					
	0	5	10	15	20	25
	Temperatures, ° C.					
0	600	600	600	650	730	1080*
5	600	620	640	700	1120*	480
10	660	700	750	1120*	1040	
15	820	840	930	1120*	810	
25	770	670	680	1000*	950	
50		1040	1080*	1050	1060	

*Approximate position of flame edge.

Table 6.--<u>Adiabatic flame temperatures of diethylenetriamine and</u>
<u>air mixtures and of unsymmetrical dimethyl hydrazine</u>
<u>and air mixtures at one atmosphere initial pressure.</u>*

DETA,** percent	UDMH,** percent	Flame temperature, °K. (Calc.)
3.0		2387
4.0		2288
5.0		2058
6.0		1766
7.0		1482
8.0		1276
9.0		1220
	11.5	1314
	17.5	1177
	31.6	974

*Calculations by E. B. Cook of this Laboratory.
**Initial temperatures of gaseous mixture:
DETA = 423° K., UDMH = 330° K.

Table 7.--(A) <u>Comparison of densities and viscosities of MAF-1 and MAF-3</u>
<u>at 25° C. with those of DETA at its boiling point.</u>
(B) <u>Comparison of temperatures of DETA at which its density or</u>
<u>viscosity equals those of MAF-1 or MAF-3 at 25° C.</u>
(C) <u>Comparison of temperatures of DETA at which its density or</u>
<u>viscosity equals those of MAF-1 or MAF-3 at 60° C.</u>

	A		B		C	
	Density,	Viscosity,	Temperatures, ° C.		Temperatures, ° C.	
Fuel	ρ, gm./cm.^{3}	η, centipoise	ρ	η	ρ	η
MAF-1*	0.869	1.22	120	80	158	138
MAF-3**	.916	3.5	60	40	98	> 100
DETA**	.785	.43				

*Correspondence: Reaction Motors Division, Denville, New Jersey.
**Ethylene Amines, Dow Chemical Company, Midland, Michigan, 1959.

Table 8.--<u>Mass spectrometric analyses of combustion products</u>
of UDMH diffusion flames.

	Diffusion flames over tray					
	5.1 × 25.4 × 1.4 cm.				76 cm.	
Sampling point, cm. above flames	0	0	0	5	0	5
Analysis, percent:						
Carbon dioxide	4.3	2.9	4.0		3.2	0.3
Carbon monoxide	3.1	2.3	3.2		1.6	0
Methane	4.0	1.3	2.4			
Formaldehyde or ethane*	.3	.1	.1		1.6**	0
Ethylene	1.8	1.2	1.2			
Acetylene	.3	.1	.3			
Methyl cyanide	.2	.1	.1	0		0
Hydrogen cyanide***	1.5	1.1	1.8	0	.7	0
Water	1.6	1.2	1.0			
Hydrogen	3.6	1.8	3.0		1.4	0
Nitrogen + argon	75.6	77.2	76.3	Air	80.5	Air
Oxygen	3.7	10.7	6.6		11.0	

*Probably ethane, since Schiff's test for aldehydes was negative.
**Total of methane, ethane, ethylene, and acetylene.
***Presence or absence confirmed by Prussian blue test for cyanides.

Table 9.--<u>Mass spectrometric analyses of combustion products</u>
<u>along axis of UDMH-air flat flames.</u>*

	UDMH, percent				
	11.5	17.5	17.5	17.5	31.6
Distance above blue flame, mm.	4	1	2	4	4
Observed flame temperature, °K.	> 1340	1240	1250	1270	1030
Analysis, percent:					
Ethylene	2.2	3.4	3.4	3.4	5.5
Hydrogen cyanide	4.4	6.2	4.5	5.6	7.2
Ammonia	.7	1.6	1.5	1.3	4.0
Carbon dioxide	1.8	.2	.5	.7	.1
Oxygen	.2	2.0	1.6	.7	1.3
Nitrogen	63.8	53.2	56.6	55.2	46.2
Methane	1.1	6.3	3.8	3.4	11.6
Carbon monoxide	13.0	11.5	12.6	14.0	8.4
Hydrogen	11.6	14.9	14.8	14.3	14.6
Argon	.8	.7	.7	.7	.6

*Data obtained by J. M. Singer of this Laboratory.

Table 10.--Fire points of fuel-water solutions.

Fuel	Temperature, ° C.	Volume percent fuel	Heat of vaporization / Heat of combustion
Tray 15 × 76 × 1.6 cm. deep			
Methyl alcohol	25	42	
	56	20	0.60
Acetone	25	15	
	60	10	.92
Isopropyl alcohol	25	40	
	66	8	1.09
Tertiary butyl alcohol	25	35	
	64	8	1.01
UDMH	33	50	
	60	34	.22
	63	34	
	Burnout*	28*	
MAF-1	34	64	
	60	39.5	.39**
	63	38	
MAF-3	25	63	
	60	53	.52**
	63	51	
Tray 5.1 × 25.4 × 104 cm. deep			
Methyl alcohol	25	49	
Acetone	25	21	
Isopropyl alcohol	25	42	

*A sufficiently concentrated solution was ignited and permitted to
    burn to self-extinction. Residual fuel concentration was
    determined by measurement of specific gravity.
**Assumed DETA in aqueous solution did not vaporize or burn.
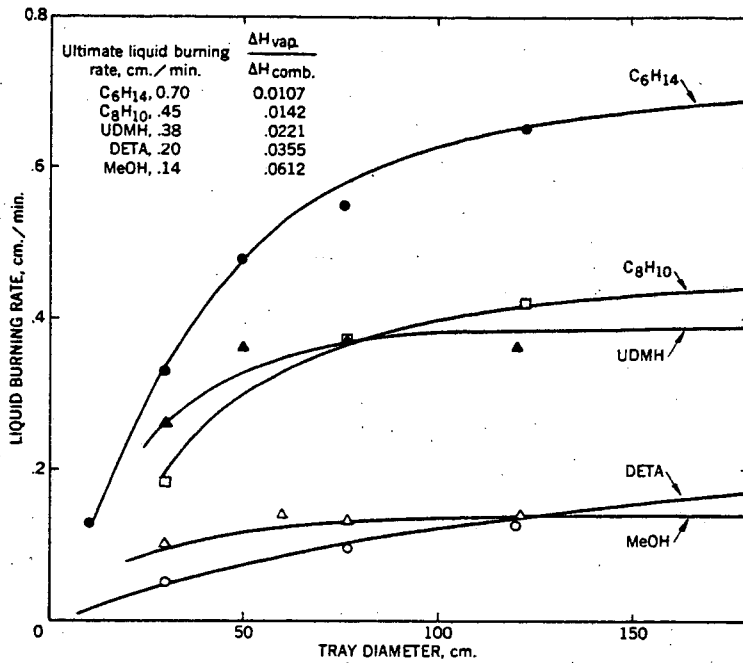
Figure 1.--Variation of Liquid Burning Rate with Tray Diameter.
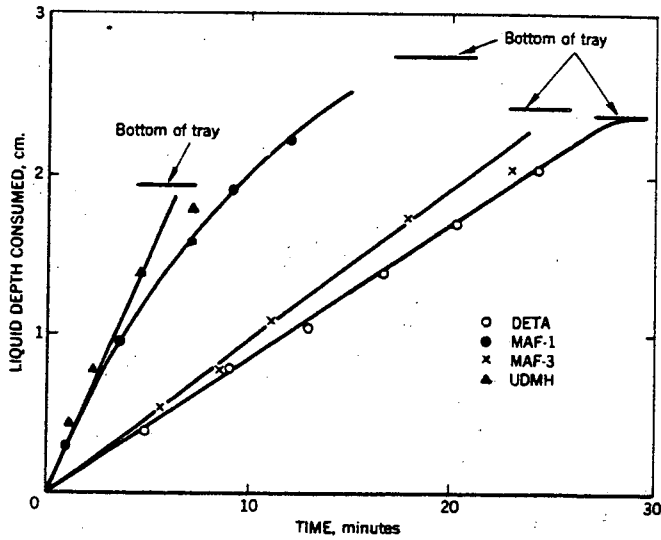
Figure 2.--Burning Time in 76 cm. i.d. Tray of
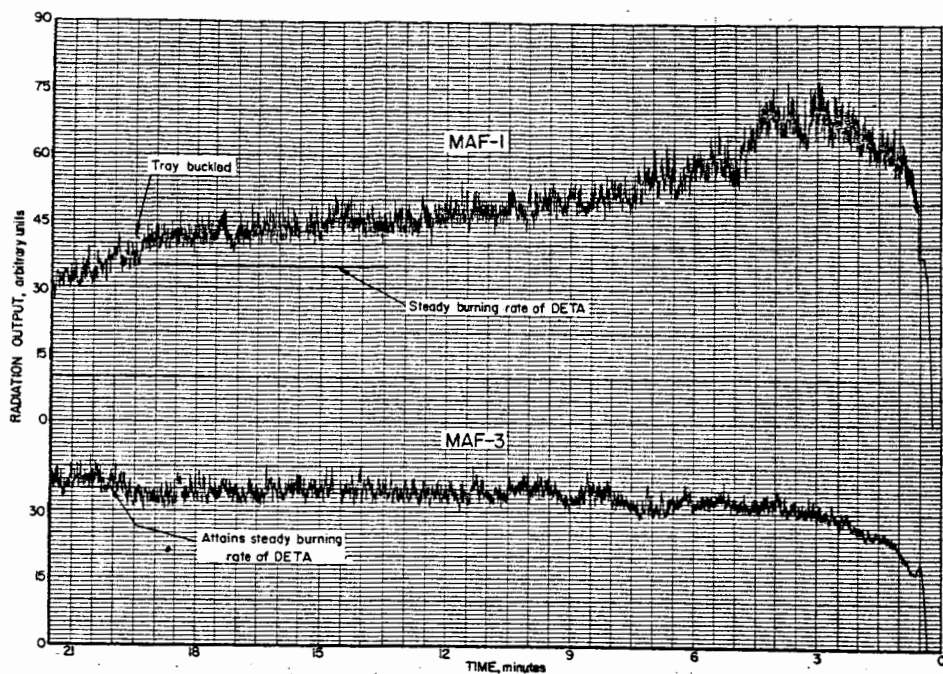UDMH, DETA, and the Blends MAF-1
and MAF-3.

Figure 3.--Radiation Records of MAF-1 and MAF-3 Burning in 122 cm. i.d. Tray.
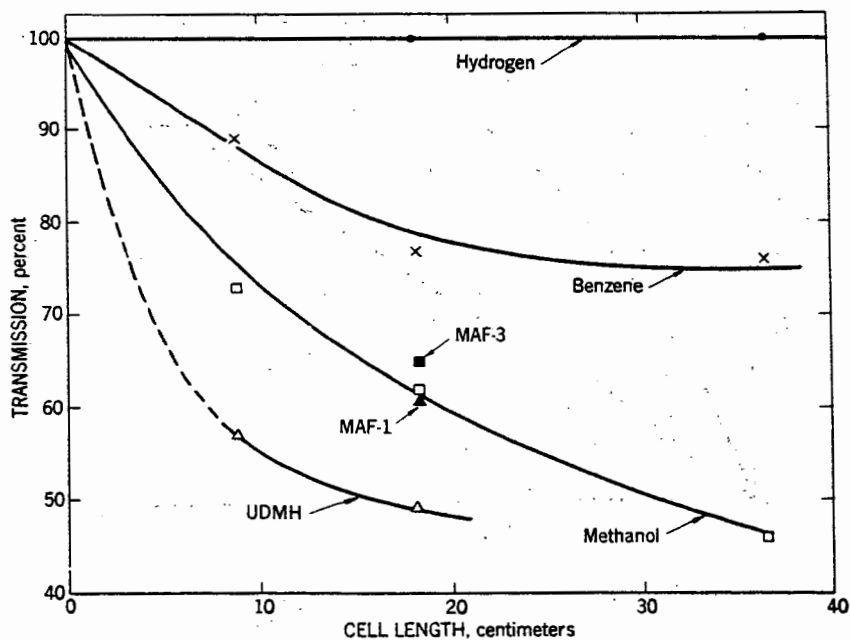

Figure 4.--Transmission of Flame Radiation Through Cells
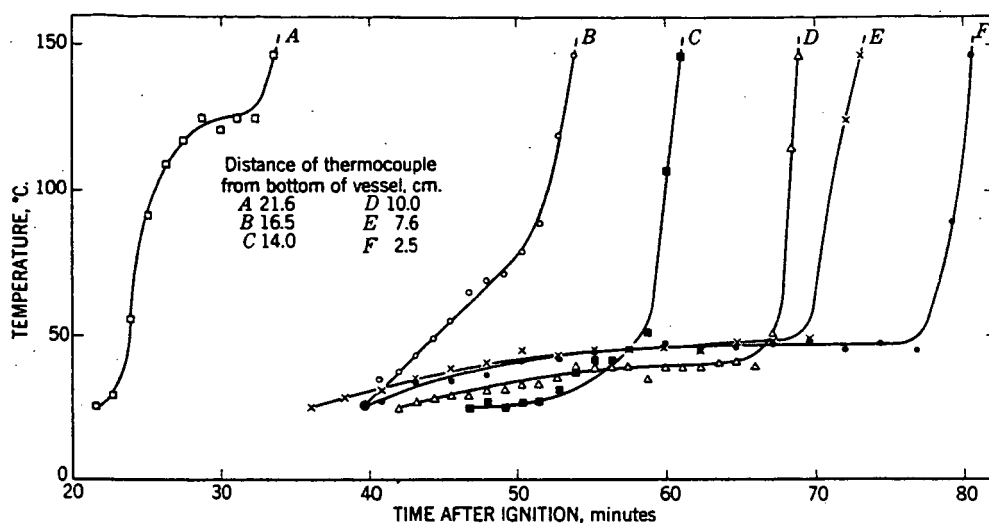Filled with Vapor of Burning Fuel.

Figure 5.--Temperature Profiles near Liquid Surface of MAF-1,
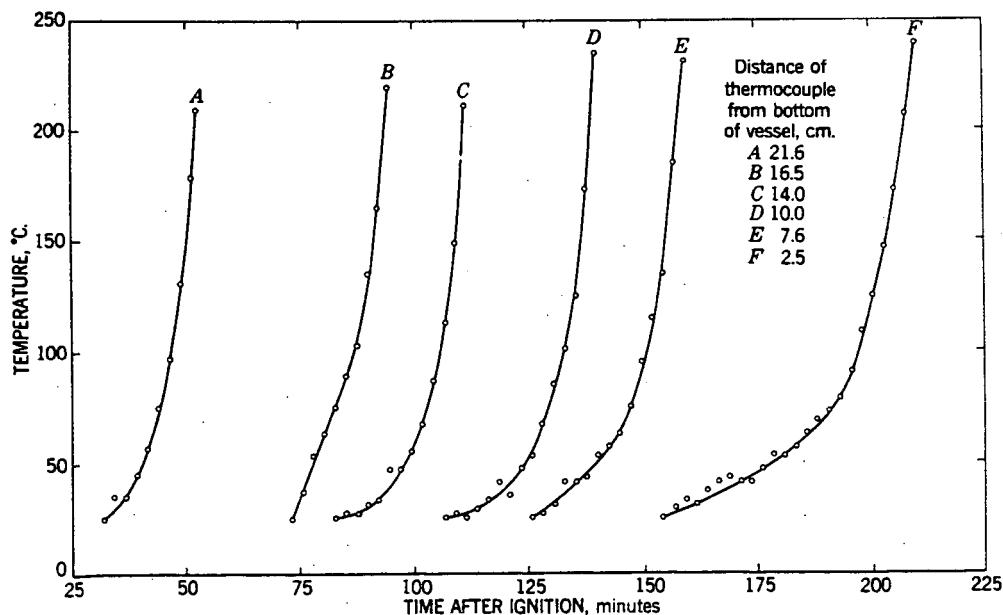Burning in 47 cm. i.d. Vessel.

Figure 6.--Temperature Profiles near Liquid Surface of MAF-3
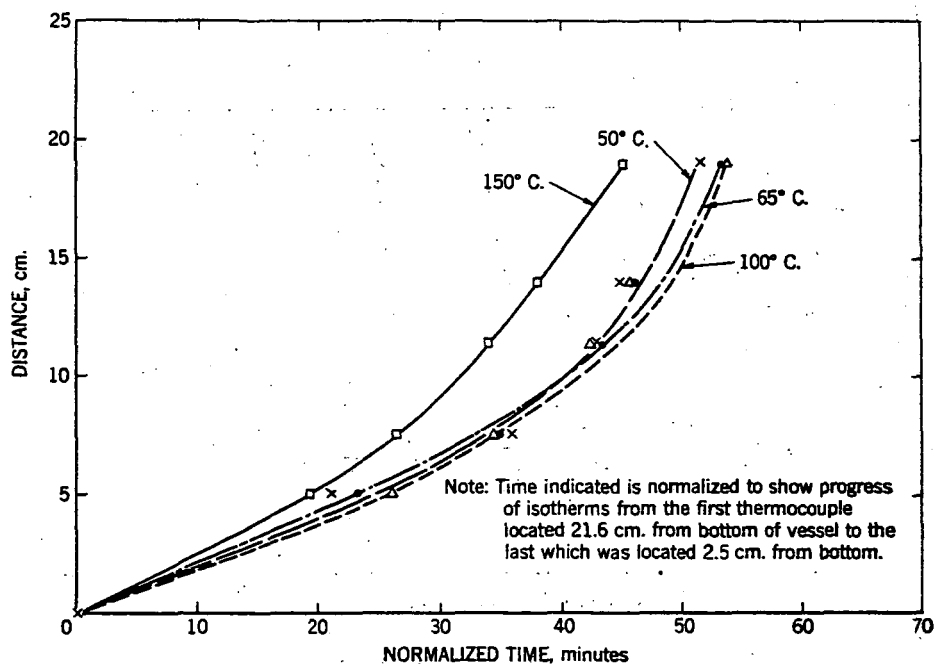Burning in 47 cm. i.d. Vessel.

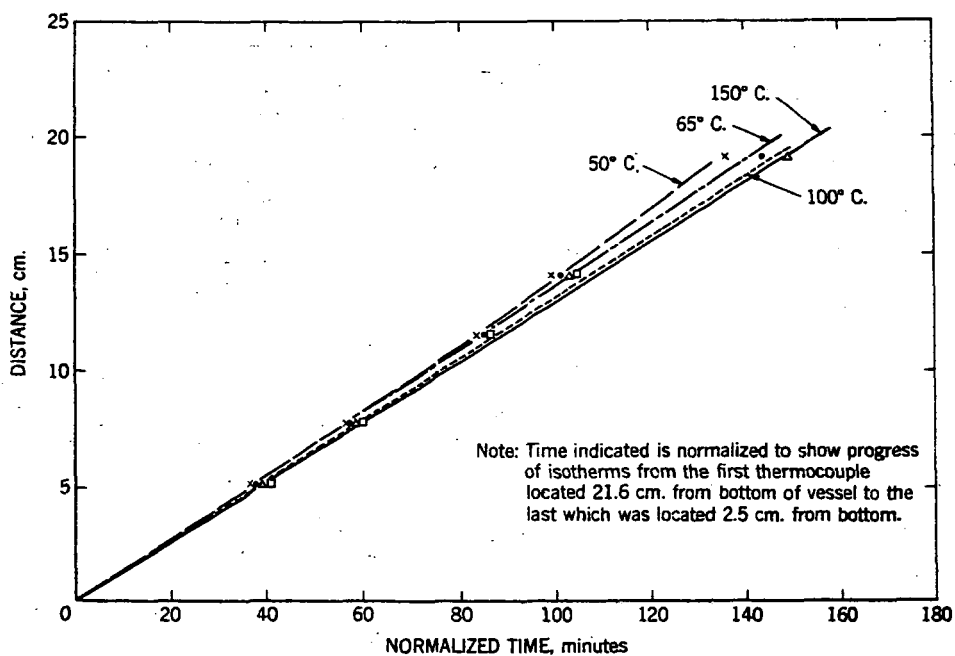Figure 7.--Progress of Isotherms Through Burning MAF-1.

Note: Time indicated is normalized to show progress of isotherms from the first thermocouple located 21.6 cm. from bottom of vessel to the last which was located 2.5 cm. from bottom.

Figure 8.--Progress of Isotherms Through Burning MAF-3.

Note: Time indicated is normalized to show progress of isotherms from the first thermocouple located 21.6 cm. from bottom of vessel to the last which was located 2.5 cm. from bottom.
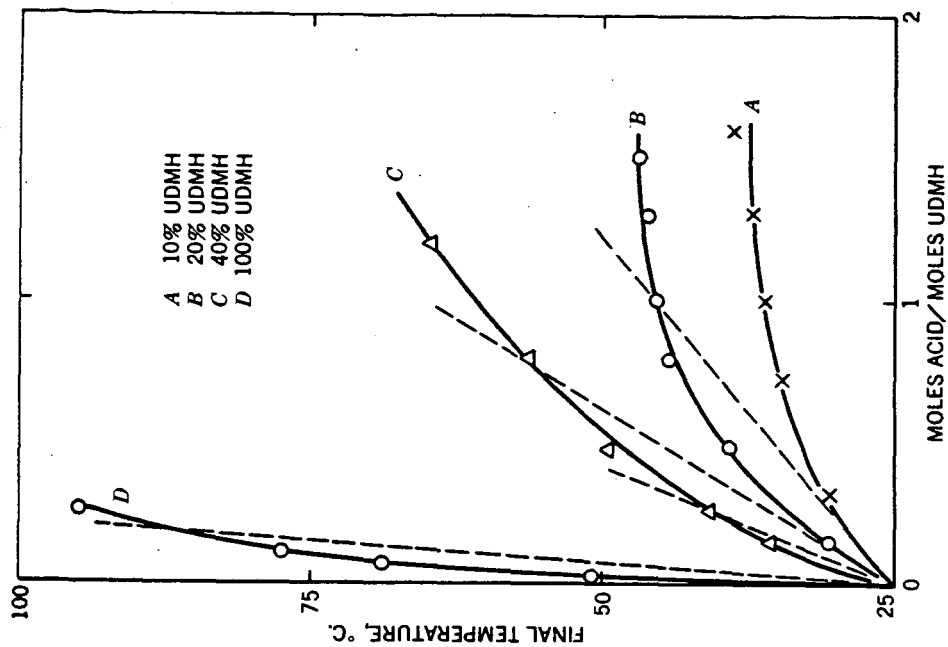
Figure 10.--Temperature Rise on Addition of Water-RFNA (50-50) to 200 cc. Water-UDMH.
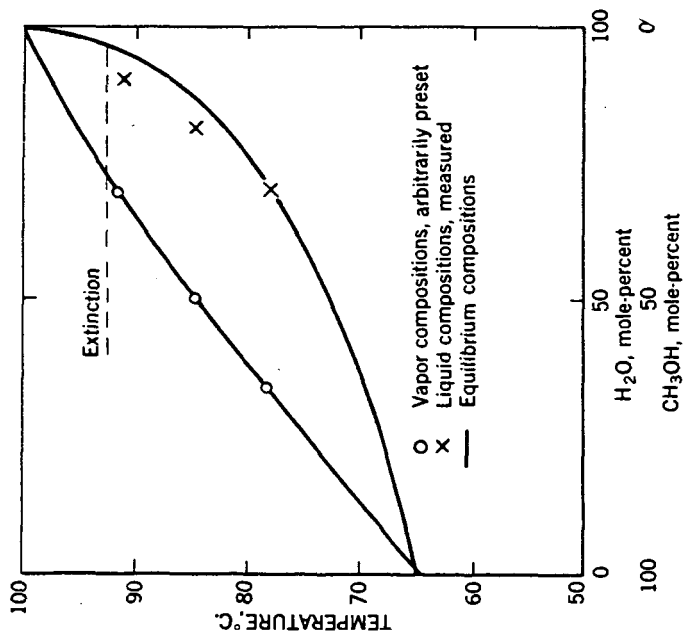
Figure 9.--Fractionation of Methanol-Water Burning in 30 cm. i.d. Tray.